GLUONS IN PROTON AND SOFT pp COLLISIONS AT HIGH ENERGIES

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The hadron inclusive spectra in pp collisions at high energies are analyzed within the soft QCD model, namely the quark-gluon string model. In addition to the sea quark distribution in the incoming proton we consider also the unintegrated gluon distribution that has an increasing behaviour when the gluon transverse momentum grows. It leads to an increase of the inclusive spectra of hadrons and their multiplicity in the central rapidity region of pp collision at LHC energies.

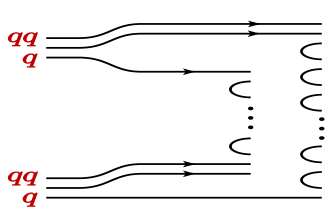
1 Introduction

As is well known, hard processes involving incoming protons, such as the deep-inelastic lepton-proton scattering (DIS), are described using the scale-dependent parton distribution functions (PDFs). Usually such distribution is parametrised as a function of the longitudinal momentum fraction x and the square of the four-momentum transfer $q^2 = -Q^2$, integrated over the parton transverse momentum k_t. However, for semi-inclusive processes, such as the inclusive jet production in DIS [1], electroweak boson production [1], etc., the parton distributions unintegrated over k_t are more appropriate. The theoretical analysis of the unintegrated quark and gluon PDFs is presented recently in [2]. According to [2], the gluon distribution function $g(k_t)$ as a function of k_t at fixed Q^2 has a very interesting behaviour at small $x \leq 0.01$, it increases very fast starting from almost zero values at $k_t \sim 0$. In some sense, $g(k_t)$ blows up when k_t increases, then, it falls down at k_t close to 100 Gev/c. In contrast to that the quark distribution $q(k_t)$, as a function of k_t, is almost constant in the whole region of k_t up to $k_t \sim 100$ GeV/c and smaller than $g(k_t)$. These parametrisations of the PDFs were obtained in [2] within the leading order (LO) and the next to leading order (NLO) approximations

of QCD at $Q^2 = 10^2$ (GeV/c)^2 and $Q^2 = 10^4$(GeV/c)^2 from known (DGLAP-evolved [3]) parton densities determined from global data analysis. At small values of Q^2 the nonperturbative effects should be considered for properly parametrising the PDFs. The nonperturbative effects can arise from the complex structure of the QCD vacuum. The instantons are one of the well studied topological fluctuations of the vacuum gluon fields, see, for example, [4]-[6] and references therein. In particular, it is shown [6] that the inclusion of the instantons results in the anomalous chromomagnetic quark-gluon interaction (ACQGI) which for the massive quarks gives the spin-flip part of it. Within this approach the very fast increase of the unintegrated gluon distribution function at $0 \leq k_t \leq 0.5$ Gev/c and $Q^2 = 1$ Gev/c is also shown.

2 Inclusive spectra of hadrons in pp collisions

Let us analyze the hadron production in pp collisions within the quark-gluon string model (QGSM) [7] or the dual parton model (DPM) [8] including the transverse motion of quarks and diquarks in colliding protons [9, 10]. As is known, the cylinder type graphs presented in Fig.1 dominate at high-energy hadronic interactions [7]. A physical meaning of the graph presented in Fig.1 is the following. The left-hand side diagram of Fig.1, the so called one-cylinder graph, corresponds to the case when two colorless strings are formed between the quark/diquark (q/qq) and the diquark/quark (qq/q) of the colliding protons, then, at their breaking the quark-antiquark and diquark-antidiquark pairs are created and fragmented to hadrons. The right hand-side diagram of Fig.1, the so called multi-cylinder graph, corresponds to a creation of the same two colorless strings stretched between valence quarks and diquarks and many strings stretched between sea quarks and antiquarks in the different protons.



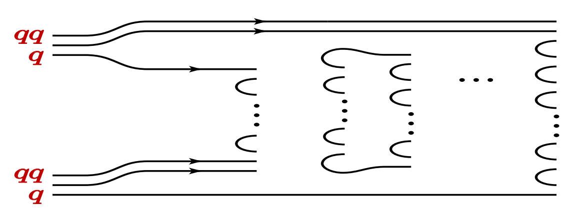


Figure 1: The one-cylinder graph (left) and the multi-cylinder graph (right) for the inclusive $pp \to hX$ process.

The inclusive spectrum of hadrons in the QGSM is written as follows [9, 10]:

$$\rho(x,p_t) \equiv E\frac{d\sigma}{d^3\mathbf{p}} = \sum_{n=1}^{\infty}\sigma_n(s)\phi_n(x,p_t) \ , \tag{1}$$

where $E, \mathbf{p}$ are the energy and three-momentum of the produced hadron h in the c.m.s. of colliding protons, $\sqrt{s}$ is the initial energy; x, p_t are the Feynman variable and the transverse momentum of h respectively; σ_n is the cross section of n cut-Pomeron interaction which is calculated within the "quasi-eikonal approximation" [11], the function $\phi_n(x,p_t)$ has the following form [9] :

$$\phi_n(x,p_t) = \int_{x^+}^{1} dx_1 \int_{x_-}^{1} dx_2 \psi_n(x,p_t;x_1,x_2) \ , \tag{2}$$

where

$$\begin{aligned}\psi_n(x,p_t;x_1,x_2) = F_{qq}^{(n)}(x_+,p_t;x_1)F_{q_v}^{(n)}(x_-,p_t;x_2)/F_{q_v}^{(n)})(0,p_t) + \\ +F_{q_v}^{(n)}(x_+,p_t;x_1)F_{qq}^{(n)}(x_-,p_t;x_2)/F_{qq}^{(n)})(0,p_t) + \\ 2(n-1)F_{q_s}^{(n)}(x_+,p_t;x_1)F_{\bar{q}_s}^{(n)}(x_-,p_t;x_2)/F_{q_s}^{(n)})(0,p_t) \ .\end{aligned} \tag{3}$$

and $x_\pm = 0.5(\sqrt{x^2+x_t^2} \pm x), x_t = 2\sqrt{(m_h^2+p_t^2)/s}$,

$$F_\tau^{(n)}(x_\pm,p_t;x_{1,2}) = \int d^2k_t \tilde{f}_\tau^{(n)}(x_\pm,k_t)\tilde{G}_{\tau\to h}\left(\frac{x_\pm}{x_{1,2}},k_t;p_t)\right) \ , \tag{4}$$

Here τ stands for the flavour of quarks and diquarks, $\tilde{f}_\tau^{(n)}(x',k_t)$ is the quark distribution function that depends on the longitudinal momentum fraction x' and the transverse momentum k_t. $\tilde{G}_{\tau\to h}(z,k_t;p_t) = z\tilde{D}_{\tau\to h}(z,k_t;p_t)$, where $\tilde{D}_{\tau\to h}(z,k_t;p_t)$ is the fragmentation function (FF) of a quark (antiquark) or diquark of flavour τ into a hadron h. We assume that both the distribution and the fragmentation functions are factorized over the longitudinal and transverse momentum. If their dependence on the transverse momentum has a Gaussian form, then the function $F_\tau^{(n)}(x_\pm,p_t;x)$ can be written as follows [9]:

$$F_\tau^{(n)}(x_\pm,p_t;x_{1,2}) = f_\tau^{(n)}(x_{1,2})G_{\tau\to h}(z)\tilde{I}_n(z,p_t) \ , \tag{5}$$

where the function $\tilde{I}_n(z,p_t)$ reads [9]

$$\tilde{I}_n(z,p_t) = \frac{\gamma_z}{\pi}\exp(-\gamma_z p_t^2), \ \gamma_z = \frac{\tilde{\gamma}}{1+n\rho z^2}, \ \rho = \frac{\tilde{\gamma}}{\gamma} \ . \tag{6}$$

Note that at $x = 0$ the function $F_\tau^{(n)}$ does not depend on n. In our calculations we have parametrized the quark distribution and FF by an exponent. In this case the function $\tilde{I}_n$ has a more complicated form. However, in this case $F_\tau^{(n)}$ does not depend on n too.

• **Gluon distribution in proton** .

As is mentioned in the Introduction, the unintegrated gluon distribution in the proton at small values of x, as a function of k_t, increases very fast when k_t increases and then slowly decreases, according to the instanton vacuum approach for the massive quarks [6] at low values of $Q^2 \sim 1$ GeV/c. The similar behaviour for $g(k_t)$ was obtained within the NLO QCD calculations at large $Q^2 = 10^2$GeV/c and $Q^2 = 10^4$GeV/c for the massless quarks [2]. This allows us to assume that at $Q^2 = 0$ and $x = 0$ the gluon distribution in proton, as a function of k_t, has a similar behaviour.

$$g(k_t) \sim k_t^{a_g} \exp(-b_g k_t) \ , \tag{7}$$

where the parameters $a_g > 0$ and $b_g > 0$.

• **Hadron production in central rapidity region**.

According to the Abramovskiy-Gribov-Kancheli cutting rules (AGK) [12], at mid-rapiditiy only Mueller-Kancheli type diagrams contribute to the inclusive spectrum of hadrons. In our approach the function $F_\tau^{(n)}$ is parametrized on such a way, that in the central region ($y = 0$), when $x \simeq 0$ and $z \simeq 0$, it becomes proportional to n and satisfies to the AGK cancellation. Thus,

$$\rho_q(x = 0, p_t) = \phi_q(0, p_t) \sum_{n=1}^{\infty} n\sigma_n(s) = gs^{\Delta}\phi_q(0, p_t), \tag{8}$$

where $\phi_q(x = 0, p_t)$, depends only on p_t. Considering the gluons from incoming protons, which may split into $q\bar{q}$ pairs, we get an additional contribution to the spectrum:

$$\rho_g(x = 0, p_t) = \phi_g(0, p_t) \sum_{n=2}^{\infty} (n-1)\sigma_n(s) \equiv \phi_g(0, p_t)(gs^{\Delta} - \sigma_{nd}) \ , \tag{9}$$

Where $\Delta = 0.12$, g=21 mb and σ_{nd} is the cross section of any number cut-Pomeron exchange. The quantities

$$\sum_{n=1}^{\infty} n\sigma_n(s) = gs^{\Delta} \ ; \ \sum_{n=1}^{\infty} \sigma_n(s) = \sigma_{nd} \tag{10}$$

were calculated in [11] within the “quasi-eikonal” approximation [11]. Assuming that one of the cut-Pomerans is always scratched between valence quarks and diquarks which are

not coming from the splitting of gluons, in Eq. (9) we excluded unity from n. Finally, we can present the inclusive spectrum at $x \simeq 0$ in the following form:

$$\rho(p_t) = \rho_q(x=0,p_t) + \rho_g(x=0,p_t) = gs^{\Delta}\phi_q(0,p_t) + \left(gs^{\Delta} - \sigma_{nd}\right)\phi_g(0,p_t)\ , \qquad (11)$$

We fix these contributions from data on the charged particles p_t distribution, parametrising them as follows:

$$\phi_q(0,p_t) = A_q \exp(-b_q p_t)\ ,\ \ \phi_g(0,p_t) = A_g\sqrt{p_t}\exp(-b_g p_t). \qquad (12)$$

The parameters are fixed from a fit to data on p_t distribution of charged particles at $y=0$: $A_q = 4.78 \pm 0.16; b_q = 7.24 \pm 0.11$ and $A_g = 1.42 \pm 0.05; b_g = 3.46 \pm 0.02$.

3 Results and discussion

In Fig.2 we illustrate how our approach works for the description of the ISR data on inclusive spectra of charged pions and kaons. The solid lines correspond to our calculations without the gluon contribution ρ_g. As one can see, we have obtained a quite good description of the spectra as functions of p_t, up to $p_t = 1.4$ GeV/c at different values of x. Though, in Fig. 2 we present results for $\sqrt{s} = 53$ GeV, but the description of data at other ISR energies ($\sqrt{s} = 23.3, 30.6, 44.6, 53$ GeV) is similarly good. The result of the fit to data on the charged hadron inclusive spectra is presented in Fig.3. The long dashed curve corresponds to the quark contribution $\rho_q(x=0,p_t)$ given by Eq.(8), whereas the short dashed line is the gluon contribution $\rho_g(x=0,p_t)$ (Eq.(9)) to the invariant yield d^3N/dyd^2p_t; the solid curve corresponds to the sum of both contributions, see Eq.(12). One can see that the conventional quark contribution $\Phi^q(y=0,p_t)$, see Eq.(12), is able to describe the data up to $\leq$1 GeV/c, whereas the inclusion of the gluon contribution allows us to extend the range of good description up to 2 GeV/c. At larger values of p_t the contribution of hard processes is not negligible and one has to take them into account based on the perturbative QCD.

4 Conclusion

Our study has shown that the soft QCD or the QGSM is able to describe the experimental data on inclusive spectra of light hadrons like pions and kaons produced in pp collisions at not large values of the transverse momenta $p_t \leq 1GeV/c$ rather satisfactorily. The inclusion of the unintegrated distributions of gluons in the proton due to instanton

vacuum excited in the strong pp interaction allows us to extend the satisfactory description of the experimental data on the inclusive spectra of charged hadrons at $y = 0$ up to $p_t \sim 2GeV/c$. At higher values of the transverse momentum the hard parton interactions should be considered for describing the experimental data.

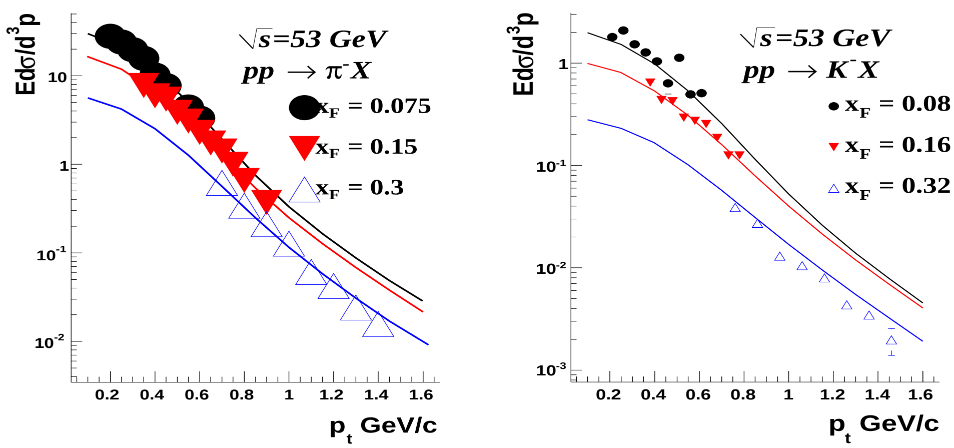


Figure 2: The inclusive spectra of π^- (left) and K^- (right) mesons in pp collision $Ed\sigma/d^3p$ [mb GeV^{-2}c^3] at $\sqrt{s}$ =53 GeV compared with the ISR data [13]. The solid lines correspond to our calculations whithout the gluon contribution ρ_g

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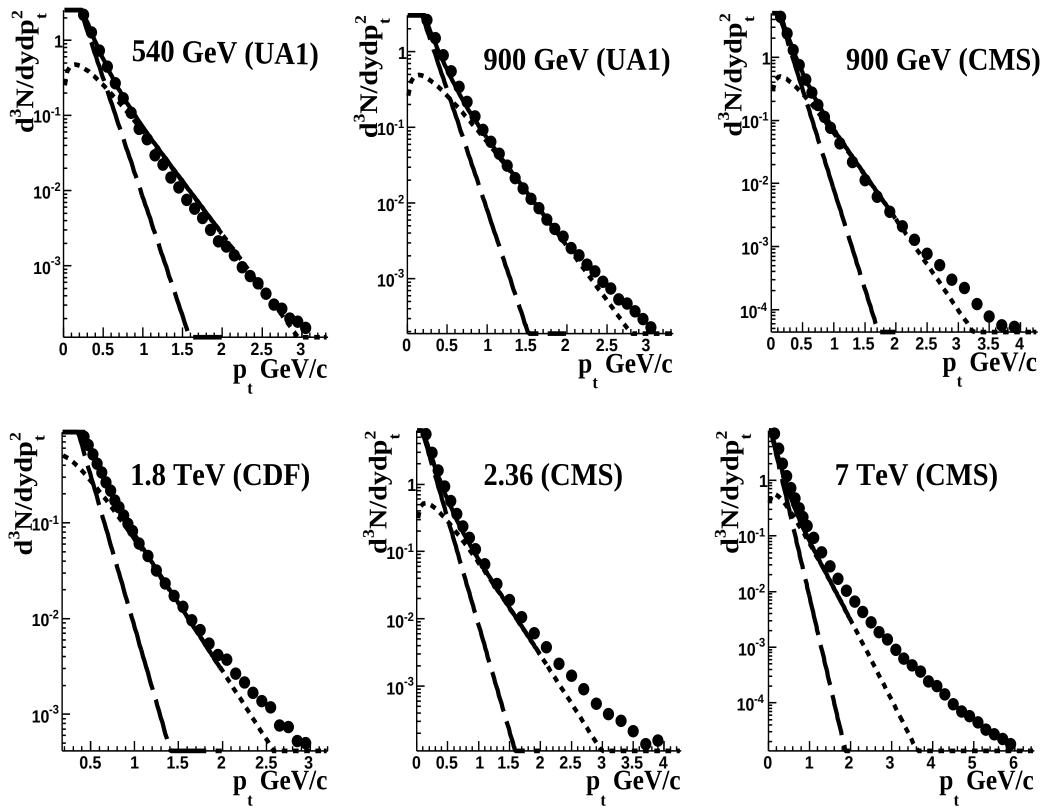

Figure 3: The charged particles yield in the central rapidity region ($y = 0$) as a function of p_t at $\sqrt{s}$=540 and 900 GeV (top) and $\sqrt{s}$=1.8, 2.36 and 7 TeV (bottom) compared with UA1, CDF and CMS data [14, 15, 16]. The long dashed curve corresponds to the quark contribution $\rho_q(x = 0, p_t)$ given by Eq.(8), whereas the short dashed line is the gluon contribution $\rho_g(x = 0, p_t)$ (Eq.(9)) to the inclusive yield d^3N/dyd^2p_t; the solid curve corresponds to the total calculation including both these contributions, see Eq.(12).